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REVIEW ARTICLE

An application- and market-oriented review on large format additive manufacturing, focusing on polymer pellet-based 3D printing

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Abstract

Since this advent, additive manufacturing (AM) has grown steadily and found applications across all types of sectors. While the great development of such technologies has improved the quality of prints and expanded the availability of materials, AM still has some limitations regarding its physical scaling. This paper will briefly present the state-of-the-art of large-scale additive manufacturing and subsequently greater attention will be given to extrusion-based 3D printing. Specifically, we will discuss about large format additive manufacturing (LFAM) or big area additive manufacturing (BAAM), a technology based on material extrusion born a few years ago. These systems are characterized by higher deposition rate and lower costs of the material compared to fused filament fabrication (FFF) printers; moreover, they allow to obtain parts with better properties (e.g., adding carbon or glass fibers). The world of research has shown great interest in large-scale material extrusion technologies, which appear to be quite competitive with conventional manufacturing processes and which will find increasing application in the industrial field. With the aim of developing a tool for orienting researchers and technicians in this complex field, the present paper presents a systematic review of the actual market of machines, the research in extrudable materials and related applications concerning large-scale 3D printing, and in particular the LFAM.

Keywords 3D printing · Large format additive manufacturing · LFAM · Pellet-based additive manufacturing · Pellet extrusion · Polymers

1 Introduction

In recent decades, additive manufacturing (AM) processes [1], also known as 3D Printing, have grown enormously, allowing parts with excellent dimensional and surface finish qualities, paving the way to applications in aerospace, automotive, medical and dental, electronics, military and defense, architecture, furniture and construction.

On the other hand, limitations still exist regarding production of large parts: commercial 3D printers have relatively low print volumes, less than 1 m^3 with low deposition rates. Most of extrusion-based 3D printers offer build volume of approximately 0.5 m^3 and build rate of 20 cm^3/h [2].

Since 2012, it has become clear that low build speeds and technical limitations tend to limit additive manufacturing to produce exclusively small parts [3]. Later articles also highlighted that one of the key aspects of the implementation of additive manufacturing technologies was linked to increase the build chamber and therefore also the print volume and the speed of the printing process [4–7].

The important role of large format additive manufacturing (LFAM) technologies in the industrial transformation known as Industry 4.0 has been underlined by various authors [8]: AM technologies will be used more in manufacturing processes due to a rapid decrease in the costs of this equipment and to a simultaneous growth in terms of speed, precision, mechanical strength, ease of customization etc. Through these technologies, it will be easier to design complex, resistant and light geometries, as well as to produce components in higher quantities and scales [9].

The goal of the next section of the present paper is to present a review of large format 3D printing technologies and devices available on the market, focusing on those based on polymer pellet extrusion (Sect. 2). Moreover, studies

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regarding the mechanical, physical and thermal characteristics obtainable with pellet extrusion technologies will be showed and solutions to prevent problems affecting these technologies (delamination, anisotropy, porosity, etc.) will be described in Sect. 3. The cited publications demonstrate the interest of the scientific community in this field. Finally, in Sect. 4, there will be a list of applications of pellet extrusion technologies in different sectors.

2 Technologies and devices for large format 3D printing

The purpose of the present section is to review the commercial LFAM technologies and devices that have been developed in recent years, considering that LFAM technologies can be defined as having a build volume greater than 1 m^3. Commercially available LFAM devices based on several AM processes defined in [1] are reported below and finally, a synoptical table is reported.

2.1 Vat photopolymerization processes

In vat photopolymerization process, a light-curable resin is stored in a tank and treated with visible or UV light to achieve its polymerization. For large-scale applications, large quantities of photopolymer and large tanks or beads are required, making this process complex and expensive to reproduce. Despite these limitations, there are examples of large printers using this technology.

The largest printers based on Vat Photopolymerization are the “Mammoth” from Materialise (Belgium) [93] and the “RSPRO 2100” from UnionTech (China) [94]. Both have a build volume over 1.1 m^3. The first printer is based on stereolithography (SLA), the second uses a digital light processing (DLP-SLA) process.

Other printers, with lower build volumes, using this technology are the “PROX 950” from 3D Systems (United States) [95] and the “LA1100 DUAL” from SondaSYS (Poland) [96].

2.2 Powder bed fusion processes

Like Vat Photopolymerization, Powder Bed Fusion processes also have some technical problems which limit the size of the build volumes: the current machines use a single-layer preheating system which is not able to realize a uniform temperature field in the whole platform when his size is larger than 1000 mm^2 and there are also some issues of low part accuracy and fabrication efficiency related to the traditional single laser scanning systems [10].

Authors in Ref. [11] have investigated processing techniques, such as the large powder bed preheating system, multi-laser scanning system, data processing software and successfully developed a system with an effective building volume of approximately 1 m^3 [97].

Other printers using this technology with large build volumes are “Aeroswift” from Aerosud/CSIR (South Africa) [98] and “AddCreator” from ADIRA (Portugal) [99]. Both printers use selective laser melting (SLM).

2.3 Material jetting

Material jetting (MJ) is an additive manufacturing method that was initially based only on the selective polymerization of liquid photopolymers [12]. MJ has recently been expanded into metal processing: droplets of molten metal are ejected onto a heated printing platform and come together to form dense metal parts with mechanical properties that can be better than those of the cast reference [13].

Some examples of large-scale devices based on MJ technology are the “Massivit 1800” and “Massivit 1500” from Massivit 3D (Israel) [100] or Mimaki’s (Japan) “3DGD-1800” [101]. These use a technology called gel dispensing printing (GDP), a combination of FFF and SLA, in which a nozzle dispenses an acrylic photopolymer gel that is quickly hardened by ultraviolet light.

The “TKF 9000” from Titomic (Australia) [102] uses the Titomic Kinetic Fusion® (TKF®) to manufacture metal parts. In the TKF® process, the metal particles are injected into a jet stream which accelerates them. The particles exit the spray nozzle and, upon colliding with the surface, they plastically deform, sticking to the surface and each other.

2.4 Binder jetting

One of the first LFAM technologies to be developed was Enrico Dini’s D-Shape (2006) [103]. This technology is similar to the inkjet powder bed method, where a binder is selectively sprayed on the printing material. The binder and sand chemically react to form a sandstone material which creates 3D parts. Surplus powder that is not a part of the structure acts as a support to the structure and once the printing process is completed, it is removed. D-Shape “DS 12 × 12 × 10” printer has a build volume greater than 1440 m^3 and produces parts with a compressive strength of up to 235–242 MPa [14].

Nowadays the leaders of large format binder jetting printers are two companies: Voxeljet AG (Germany) and ExOne (United States), recently acquired by Desktop Metal. Both provide sand 3D printing equipment and are widely used for the production of industrial casting molds. Voxeljet AG has developed the “VX 4000” [104], the largest industrial 3D printer for sand molding worldwide, with a build volume greater than 8 m^3. The “S-Max Pro” from ExOne (Germany) [105] has a lower build volume: 1.26 m^3 and is compatible with a variety of metal, ceramic and composite materials. The systems offered by the two companies are quite similar and differ only in terms of technical specifications, such as resolution, speed or the presence of more than one print chamber (as it is for ExOne) [15].

2.5 Sheet lamination processes

In the sheet lamination method, individual cross-section layers are cut out and then laminated together using diffusion binding, low melting point alloys, adhesive polymers or ultrasound. A variety of complex shapes, cooling channels, honeycomb structures and spherical shells with holes have been built with this technology [16], which still has technological limitations that greatly increase the costs of large-scale equipment.

The only example of a sheet lamination process LFAM device is the "Soniclayer 7200" from Fabrisonic LLC (United States) [106]. Fabrisonic 3D printing technology involves using ultrasonic sounds to merge layers of metal foil and features a 3-axis Computerized Numerical Control (CNC) mill.

2.6 Directed energy deposition processes

There are various examples of LFAM machines which use DED processes to produce metal 3D printed parts.

There are three types of technologies that use Directed Energy Deposition (DED) which can be applied in LFAM:

- Electron-beam additive manufacturing (EBAM), in which a wire is used as raw material and deposited layers are joined through the application of an electron beam in a vacuum.
- Laser deposition welding (LDW) in which a metal powder is feed via a nozzle and a laser creates a weld pool on the component surface.
- Wire arc additive manufacturing (WAAM) works by melting metal wire using an electric arc as a heat source. The process is controlled by a robotic arm and the shape is built on a base plate from which the part is separated once the process is complete. The wire, when melted, is extruded in the form of beads on the substrate. As the beads stick together, they create a layer of metal material and the process is then repeated until the metal 3D part is complete.

Machines which use EBAM technology are "System III" from ADDere (United States) [107] with a build volume of 64 m^3, and "EBAM 150", "EBAM 200" and "EBAM 300" with build volumes from 7 to 9 m^3. These last printers are produced by Sciaky, Inc. (United States) [108].

Examples of machines using LDW are the "MX-Grande" from InssTek (South Korea) [109], with a build volume of 4 m^3, the "LENS CS 1500" from Optomec (United States) [110] and the "L-Series" from FormAlloy (United States) [111]. These last three machines have build volumes slightly over 1 m^3.

MX3D (Netherlands) [112] has developed the first dedicated robotic WAAM software to enable end-to-end LFAM metal printing.

2.7 Extrusion-based systems

When we refer to the extrusion-based systems, we can mention different technologies through which different materials can be extruded, such as polymers, composites, concrete, or construction materials.

LFAM extrusion-based technologies are very useful in the construction industry [14, 17], which was suggested since the late 1990s [18]. One of the most important technologies in this sector is contour crafting (CC), an additive manufacturing technology, developed since 2012 [19], that uses computer control to construct free-form building structures by repeatedly laying down layers of material such as concrete. This process can create a smooth and accurate planar or free-form surfaces.

The Chinese company WinSun [113] uses CC to print houses with a cement recipe made from recycled materials. Other examples of machines using similar technologies are the "P1" from BetAbram (Slovenia) [114], the "Big 3D-Printer 2156" from Imprimere AG (Switzerland) [115], the "S-6044 LONG" from AMT-SPECAVIA (Russian Federation) [116] and "Vulcan II" from ICON (United States) [117]. WASP's (Italy) "BigDelta" [118] has a system that only moves the extruder, reducing energy consumption and allowing quick and easy assembly. The system can print concrete, lime-based mixes, sawdust, polystyrene and enable the production of housing units with materials found in the area, with a cost tending to zero.

The CC process is limited to vertical extrusion and does not literally yield 3D structures, but rather 2.5D (vertical extensions of a planar shape) [20]. To solve this problem, robotics arms, with the extruder installed on them, are used. These systems are becoming one of the most important tools for LFAM due to their great software and hardware flexibility [21].

Examples of systems using robotics arms are the "Maxi Printer" from Constructions-3D (France) [119] and the "Cybe RC 3DP" from Cybe (Netherlands) [120].

FFF is the most widely used extrusion-based technique. The average workspace of these machines is often less than 1 m^3 [22]. This happens because the use of filaments with diameters of from 1.75 to 2.85 mm as raw material limits the build rates [23] and volumes [24].

There are several LFAM printers using FFF technology, but their build volumes are not so high and remain relatively close to 1 m^3. The "Jupiter" from ATMAT (Poland) [121] offers a large, thermo-insulated build volume of 2 m^3, whereas the other existing printers, such as the "400 Series Workbench Xtreme" from 3D Platform (United States) [122], the "BigRep One V3" from BIGREP (Germany) [123], the "F1000" from CreatBot (China) [124] and the "DeltaWASP 60100" from WASP (Italy) [125] have a smaller build volume.

For the production of parts with large print volumes, it is advisable to use pellet-based technologies. In these systems, there is a screw that conveys the thermoplastic pellet into a heating element where it melts and then the liquid material is extruded trough a nozzle [25] (Fig. 1).

There are several studies that demonstrate the advantages of this technology: production times can be reduced by up to 200 times [27], and the filament-extruding process is not required, so the costs of the raw material can be reduced by a factor of greater than 10 compared to FFF [28]. Other advantages of pellet-based systems are the ability to use an enormous variety of materials (all industrial polymers can be found as pellets) [29] and produce composites, adding elements, such as fibers and metal particles [30].

A system using pellet-based technology was developed in 2015 by Cincinnati Incorporated (USA) [126] together with Oak Ridge National Laboratories (ORNL) (USA). This is a gantry-system called big area additive manufacturing (BAAM) [2] with a build volume of over 25 m^3 and a single screw polymer extrusion nozzle that is mounted on it (Fig. 2).

Subsequently, other similar systems with really large manufacturing volumes were produced, including components useful for post-processing (milling, inspection, trimming etc.). Examples are the "MasterPrint" from Ingersoll (United States) [127], the "LSAM" from Thermwood (United States) [128], the "MILLE-500XL" from MilleBot (United States) [129] or "CFAM Prime" from CEAD B.V. (Netherlands) [130].

Other examples of pellet-based systems with lower build volumes are "The Box" printers from BLB Industries (Sweden) [131], the "Super Discovery" from CNC Barcenas (Spain) [132], the "Atlas 3.6" from Titan Robotics (United States) [133] and the "DeltaWASP 3MT Industrial 4.0" from WASP (Italy) [134].

Finally, it is important to mention the developments made by Stratasys with his "Infinite Build 3D Demonstrator", a thermoplastic pellet extrusion system that theoretically allows to print objects of infinite length. This is an 8-axis system that has been successfully tested by Ford Motor Company and Boeing for the production of lightweight parts and for the development of innovative materials [135].

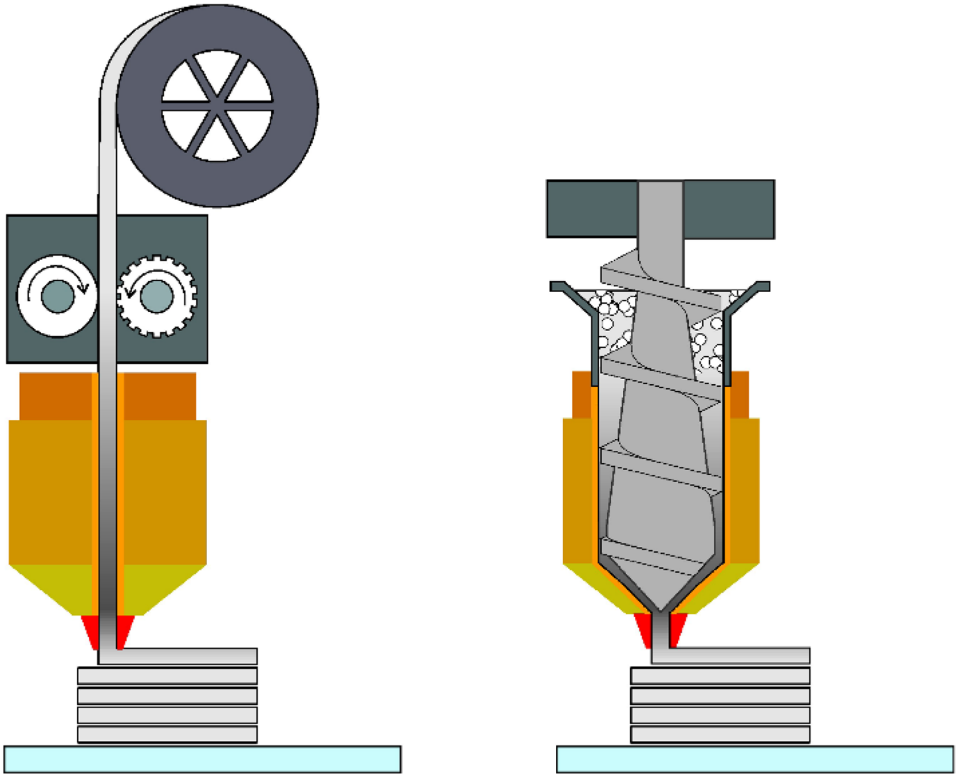

Fig. 1 On the left, the FDM operating diagram, on the right, the pellet-based operating diagram [26]

Fig. 2 BAAM system (Cincinnati Incorporated)

	Model	Brand	Technology	Build volume [m^3]	Release date
Vat photopolymerization processes	Mammoth	Materialise	SLA	1.1	2014
	RSPRO 2100	UnionTech	DLP-SLA	1.1	2019
	PROX 950	3D Systems	SLA	0.6	2014
	LA1100 DUAL	SondaSYS	DLP-SLA	0.6	2017
Powder bed fusion processes	HRPS-VII	Wuhan Binhu	SLM	0.98	2014
	Aeroswift	Aerosud/CSIR	SLM	0.7	2019
	Addcreator	Adira	SLM	0.5	2016
Material jetting	Massivit 1800	Massivit 3D	GDP	3.2	2018
	Massivit 1500	Massivit 3D	GDP	2.5	2018
	3DGD-1800	Mimaki	GDP	2.9	2020
	TKF9000	Titomic	TKF	40.5	2018
Binder jetting	DS 12 × 12 × 10	D-Shape	Binder jetting	1440	2006
	VX 4000	Voxeljet AG	Binder jetting	8	2015
	S-Max Pro	ExOne	Binder jetting	1.26	2019
Sheet lamination process	Soniclayer 7200	Fabrisonic	Lamination	3	2016
Directed energy deposition processes	System III	ADDere	EBAM	64	2020
	EBAM 300	Sciaky, Inc	EBAM	8.5	2016
	EBAM 200	Sciaky, Inc	EBAM	7.5	2020
	EBAM 150	Sciaky, Inc	EBAM	7	2020
	MX-Grande	InssTek	LDW	4	2016
	LENS CS 1500	Optomec	LDW	1.2	2016
	Lasertec 125 3D Hybrid	DMG MORI	LDW	1.15	2019
	L-Series	FormAlloy	LDW	1	2017
		MX3D	LDW	8	2014

	Model	Brand	Technology	Build volume [m^3]	Release date
Extrusion-based systems (construction industry)	P1	BetAbram	CC	328	2017
	Big 3D-Printer 2156	Imprimere AG	CC	215	2017
	S-6044 LONG	AMT-SPECAVIA	CC	58	2018
	Vulcan II	ICON	CC	57	2020
	BigDelta	WASP	Delta system	432	2017
	Maxi Printer	Constructions-3D	Robotic arm	1050	2017
	Cybe RC 3DP	Cybe	Robotic arm	50	2018
Extrusion-based systems (FFF)	Jupiter	ATMAT	FFF	2	2018
	400 Series Workbench Xtreme	3D Platform	FFF	1.05	2017
	BigRep One V3	BgRep	FFF	1	2015
	F1000	CreatBot	FFF	1	2019
	DeltaWASP 60100	WASP	FFF	1.2	2015
Extrusion-based systems (pellet-based)	BAAM	Cincinnati Incorporated	Pellet extrusion	25	2018
	MasterPrint	Ingersoll	Pellet extrusion	48	2018
	LSAM	Thermwood	Pellet extrusion	56	2018
	MILLE-500XL	MilleBot	Pellet extrusion	15.36	2018
	CFAM Prime	CEAD	Pellet extrusion	12	2018
	The Box Large	BLB Industries	Pellet extrusion	6	2019
	Super Discovery	CNC Barcenas	Pellet extrusion	3.25	2019
	Atlas 3.6	Titan Robotics	Pellet extrusion	3	2020
	DeltaWASP 3MT Industrial 4.0	WASP	Pellet extrusion	1.2	2019

3 Material and process parameters development for large format 3D printing

As mentioned, the most important technologies based on material extrusion are FFF (for low build volumes) and pellet-based technologies (for high build volumes). Unlike FFF [31], this last technology, created a few years ago, requires studies on printing materials to guarantee improvements in properties, prevent errors, such as deformations and delamination, and obtain stable processes [24].

3.1 Rheological behavior

Understanding the rheological behavior of materials is important to identify the most suitable process parameters, such as extrusion temperature, screw speed, and percentage of fibers. For this purpose, several studies have been conducted on different printing materials: acetyl–butyl styrene (ABS) [32], polyphenylene sulfone (PPSU) [31, 33], polyetherimide (PEI/ULTEM) [34], polyethersulfone (PES), polyphenylene sulfide (PPS) [35], polyetherketoneketone (PEKK) [36], polyester and vinylester [37]. These studies considered the addition of carbon (CF) or glass (GF) fibers to polymers to evaluate their influence on the rheological properties of the materials and on the glass transition temperature (Tg) [38]. Furthermore, the identification of the extrusion temperature limit to avoid the degradation of polymers, and the effect of variations in temperature and shear rate on the rheological properties of the materials were considered.

3.2 Mechanical properties

In addition to the print size, a factor which limits the applications of 3D printing in the industrial sector concerns the low mechanical properties and the anisotropic behavior of the parts. The anisotropic behavior results in a different strength of the 3D printed part when subjected to tensile or compressive stresses in the horizontal direction compared to the horizontal one. This behavior is due to the microstructure of the material within each layer which is different than that of the boundaries between the layers [39].

Traditionally, in material extrusion processes, low-temperature thermoplastics, such as polylactic acid (PLA), ABS and polycarbonate (PC), were conventionally used. Parts printed with these materials have poor strength and elongation, so the main use of these technologies was related to prototype manufacturing.

Recently, many new materials for 3D printing have been developed, such as nanomaterials, composites, biomaterials, smart materials and even fast-drying concrete [36, 38, 40].

Technical polymers, such as ultem, PPSF, nylon, Polyether Ether Ketone (PEEK) and PEKK, have also been developed, which guarantee mechanical, physical and thermal properties better than traditional materials used in extrusion processes [41].

Furthermore, it has been shown that adding fibers to the pellet guarantees better mechanical properties [42] but also leads to strong anisotropy [27]. This phenomenon was also observed by ORNL and Techmer Engineered Solutions (TES) [43], which studied the performance of various extruded materials with a BAAM system, comparing them with those obtained with injection molding or by Yeole et al. [44], who evaluated the use of carbon fiber-reinforced PPS for LFAM applications.

A "Z-Tamping" system, which compacts each deposited bead, limits the formation of voids and increases the cohesion between the layers, which can reduce the porosity and improve the mechanical properties. In this design, the extruder is in the center of an air-cooled platen that vibrates at approximately 20 Hz, flattening the layers [27].

This system is even more effective when coupled with IR lamps to increase the temperature of the deposited layers to a value just above Tg, before extruding other material onto them [45] (Fig. 3).

3.3 Delamination and distortion control

In 3D printing with thermoplastics, the melted material is deposited by the nozzle on a previously deposited layer. Therefore, when the extruded material cools below the glass transition temperature (Tg), it tries to contract, but this effect is blocked by the previous layer which is already completely cooled (contracted). This process generates stress between layers [46] which tend to accumulate on subsequent ones causing deformation and delamination [43, 44].

It has been proved that thermal distortions depend on the deposition time for each layer and on the maximum size of the part on the horizontal plane [48], which shows that this problem significantly affects LFAM processes. To predict the residual stress, deformation, and damage/delamination in these systems, a computational modeling technique can be used [47].

The problem of delamination can be reduced by heating the printing bed to a temperature at least equal to Tg and carrying out the printing process in a closed chamber [49], as happens in common FFF printers. Although it is possible to build an extremely large heated chamber that can enclose the pellet extrusion system, this would limit its flexibility and it would be difficult to control the temperature inside it [2].

It must also be considered that to avoid deformations following the deposition of the new layer, the temperature of the substrate must remain below a threshold value [50].

It has been observed that the addition of CF to the polymer pellet can eliminate the need to control the printing temperature in a heated chamber ensuring a reduction in distortion [42]. In fact, a thermal analysis conducted with an IR camera showed that the addition of CF increases the extrusion temperature, and the deposited layers remain hot for a longer time [51].

Another approach to mitigating distortion is to reduce the deposition time for each layer. This can be achieved using a high extrusion rate [52] or a continuous toolpath algorithm to reduce extrusion starts and stops [53].

An alternative can be a real-time optimization of the deposition time of each layer (layer time) based on the surface temperature predictions of the 3D printed parts [54].

3.4 Porosity control

Porosity affects both FFF technology and, on a larger scale, pellet-based technology: the deposition of oval beads involves the formation of triangular voids between adjacent beads, this phenomenon can significantly degrade the mechanical bond and reduce overall performance of the printed part [55].

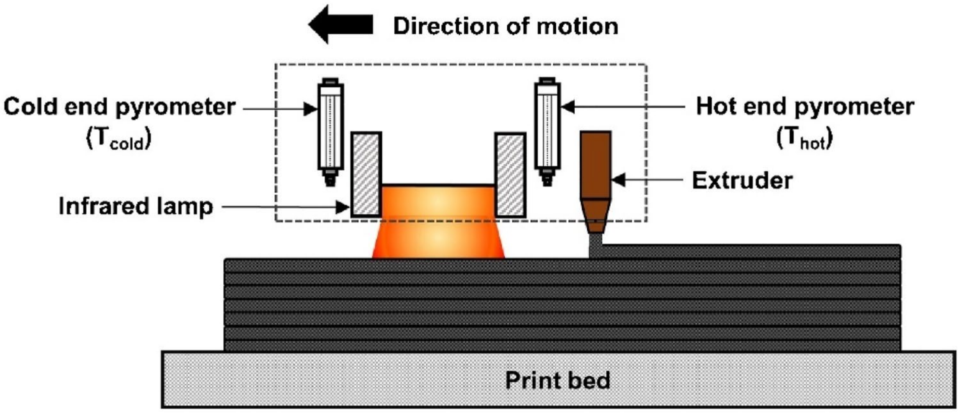

Fig. 3 Scheme of the experimental setup including IR lamps [45]

Furthermore, as previously highlighted, the addition of fibers has several advantages but increases internal porosity [27]. This may be because, contrary to what happens in FFF where the fibers align with the direction of the tool path [56], this does not happen in the pellet-based process, in which the fibers maintain a random orientation in the deposited material.

As mentioned, a "Z-Tamping" system has been used on LFAM devices to reduce the porosity. This system forces the deposited beads into nearby pores while it is still warm and pliable, resulting in a more uniform deposit surface [27].

3.5 Geometric and surface qualities

It is clear that LFAM have some disadvantages from this point of view: the actual devices use only one extruder, for this reason support removal could be difficult and there's also a poor surface finish due to the large size of the bead and the high layer height.

The surface quality and the dimensional accuracy can be improved by optimizing process parameters: the values of layer thickness, printing speed, melt flow and pressure inside the cylinder in which the screw rotates are very important from this point of view. However, post-processes are often required to obtain a better surface of the parts: these include simple milling [57] or more complex processes as done for the production of a 3D printed Shelby Cobra [58]. In this case, in fact, once the printing was completed, the body of the vehicle was machined and sanded and finally, after filling and polishing, the paint was applied.

A method to reduce these problems can be the use of a nozzle that allows printing with two different resolutions, with the addition of a "Positiverter" to improve the starting and stopping of the extrusion [59] (Fig. 4).

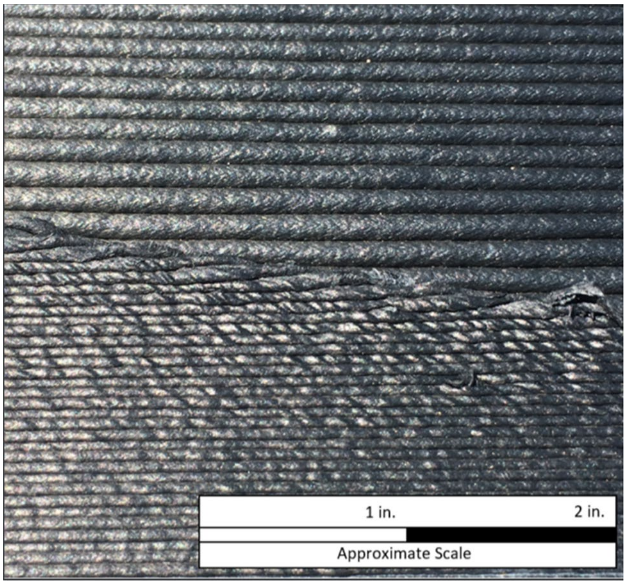

Fig. 4 Print with different resolution [59]

Another problem which causes a high surface roughness or mattness is called "Sharkskin". The onset of such defects depends on several factors: the structure of the extruded polymer matrix, flow rate, temperature etc. Studies have shown that this phenomenon is especially linked to the transition from viscous to more elastic behavior as the shear rate increases [60].

3.6 Use of recycled and bio-derived materials

An interesting aspect of pellet-based extrusion technologies is the possibility of using plastic waste as raw material for the manufacture of filaments, as occurs in Recyclebot systems [61], or for the direct production of parts.

Recyclebots have successfully recycled several thermoplastic filaments including PLA [62–64], high-density polyethylene (HDPE) [64], ABS [64], elastomers [64] and carbon fiber reinforced polymers [64]. It has been shown that using these systems it is possible to reduce the energy embodied in the 3D printing filament by 90% compared to the production of traditional filaments [62, 65, 66]. It must be considered that melt and extrusion cycles affect the mechanical properties of the polymers [67], this limits the recycling cycles to five before reinforcement or blending with virgin materials becomes necessary [68].

To minimize the count of melting and extrusion cycles of recycled plastic it is possible to print directly from a variety of sources, such as plastic pellets, plastic flakes, regrind or recycled plastic fragments, obtaining properties comparable to those obtainable using virgin materials [69–71]. In this case, particular attention must be paid to contamination and moisture which can cause deterioration of the physical and chemical properties of the polymers [72] (Fig. 5).

Finally, another application is the use of bio-derived materials such as wood fiber. Using these sustainable alternatives in 3D printing allows to improve the properties of printed parts, while providing an environmentally friendly alternative to carbon or glass filled polymer matrices, all at reduced material costs [73].

Also in this case, to obtain satisfactory properties, appropriate precautions must be taken: a good interaction between matrix and filler must be achieved, the percentage of filler has a limit that must not be exceeded to avoid occlusions of the extruder, high shear rate can result in backpressure which can result in inconsistent bead size and poor surface quality [57] and furthermore the pellet must be dried before printing to avoid problems related to moisture [74].

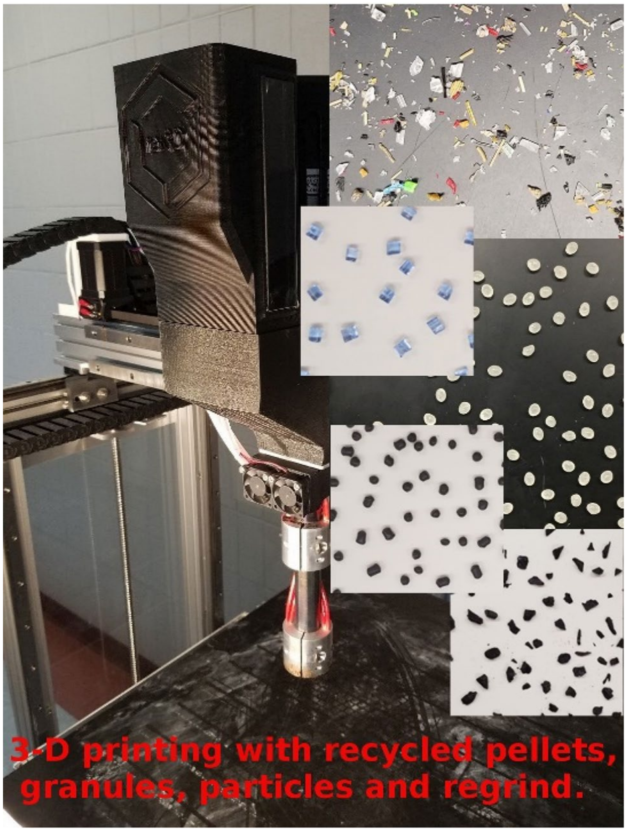

Fig. 5 Gigabot X prototype that can 3D print pellets, granules or recycled materials [70]

4 Large format pellet-based extrusion applications

As highlighted in the previous sections, pellet-based additive manufacturing technologies have significant advantages for large-scale production. In recent years, these technologies have aroused great interest in the research sector, as seen in Sect. 3. In this section, some case studies will be discussed that highlight the advantages of this technology.

4.1 Automotive

The American company Local Motor (LM) was one of the first to exploit the advantages of pellet-based extrusion technologies [75]. The excellent results in terms of costs and manufacturing times have prompted Local Motors to start the production of vehicles manufactured with pellet-based extrusion technologies. In 2016, LM released “Olli” [136], an electric self-driving shuttle whose structure is about 80% 3D printed (Fig. 6).

LFAM technologies also have the advantage of being usable for rapid prototyping of vehicles for evaluation and development purposes. For example, a BAAM system was combined with a hardware-in-the-loop (HIL) system: the powertrain and vehicle controls models were developed in the HIL environment and were integrated into the vehicle’s CAD model, which was subsequently printed with BAAM technologies [58, 76].

Fig. 6 3D printed vehicle “Olli”, Local Motors

BAAM technologies can be very useful for tooling or direct replacement of parts. There are several examples of automotive molds or tooling produced with this technology [77, 78]. Interestingly, the entire body of a 1953 Jeep Willy [77] was designed, printed and assembled in less than 1 month.

4.2 Naval industry

The limits of AM technologies linked to the resistance of the materials and the print volumes have not allowed their application in this sector, which has always been closely linked to experience and tradition. The introduction of these technologies in this sector took place only in recent years, in the so-called Shipyard 4.0 [79].

One of the most popular applications of LFAM is the University of Maine 3D-printed boat called “3Dirigo” [137], which in 2019 received three Guinness World Records for the world’s largest prototype polymer 3D printer, largest solid 3D-printed object and largest 3D-printed boat (Fig. 7).

In 2017, ORNL in collaboration with the US Office of Naval Research developed a 9 m prototype submarine hull printed in ABS-CF [138]. Thanks to BAAM technologies, considerable savings in terms of production times have been achieved and costs have also been reduced by 90%.

It must be considered that traditional boat production is quite complex and requires the manufacture of a mold. ORNL and Alliance MG [80] explored the feasibility of using BAAM to directly manufacture a catamaran boat hull mold. Once printed, it was CNC-machined to achieve the

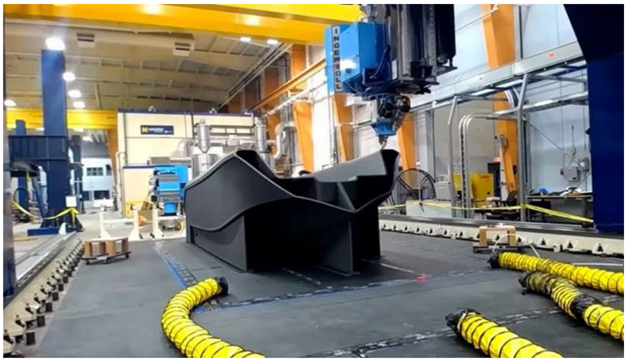

Fig. 7 Image during the 3Drigo boat printing process

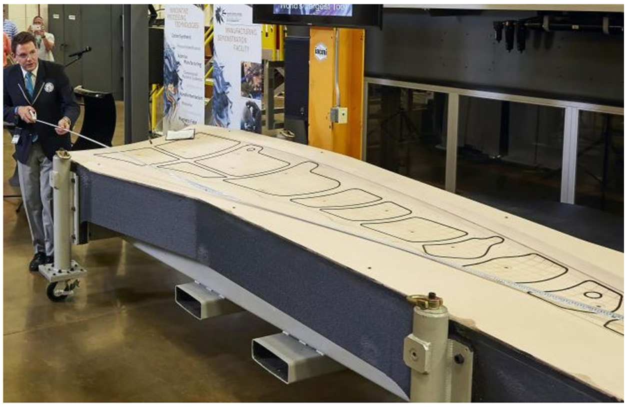

Fig. 8 The 3D printed trim tool co-developed by Oak Ridge National Laboratory and The Boeing Company. Credit to: Carlos Jones/Oak Ridge National Laboratory, U.S. Dept. of Energy

desired surface finish and finally a complete test was performed on the mold which involved the construction of the hull.

Another interesting application is that of the Swedish company Pelle Stafshede, which produces 3D-printed kayaks with corn and wood pellet [139].

4.3 Aerospace

As already highlighted in other sectors, the use of LFAM technologies can be useful for the production of molds and tools. These applications also affect the aerospace sector. In 2016, ORNL 3D printed a trim-and-drill tool [140] to produce a wing part of a Boeing 777x aircraft (Fig. 8).

These technologies have also been used to manufacture in-autoclave tools used in manufacturing aerospace composite parts [81, 82]. The results of these studies show that increasing the percentage of fibers very much influences the tensile strength and that there were no critical deformations in the tools after use.

4.4 Construction sector

ORNL in partnership with Skidmore, Owings and Merrill (SOM) [83] designed and manufactured a single-room building module with an area of almost 20 m^2. About 80% of the house was built with BAAM technology in ABS reinforced with CF. The construction of this building was part of a greater project called Additive Manufacturing Integrated Energy (AMIE) [84], which involved the integration of a hybrid vehicle and a photovoltaic system. On sunny days, the photovoltaic system meets the building's energy needs and can also recharge the vehicle's battery, in the night or on cloudy days; on the other hand, the energy accumulated by the secondary use battery storage system can be used or it can be taken from the grid (Fig. 9).

LFAM technologies were used to manufacture a facade shading system for an overlay pavilion at Expo 2020 in Dubai [85]. To select a printing material that met the aesthetic and performance requirements (especially in terms of resistance to high temperatures), tests were conducted in a climatic chamber of the Politecnico di Milano. A high temperature (HT) PLA with 5% of wood fibers was chosen.

Another application can be the production of precast concrete, which traditionally are made of wood with slow and expensive processes. ORNL and Gate Precast [86] have

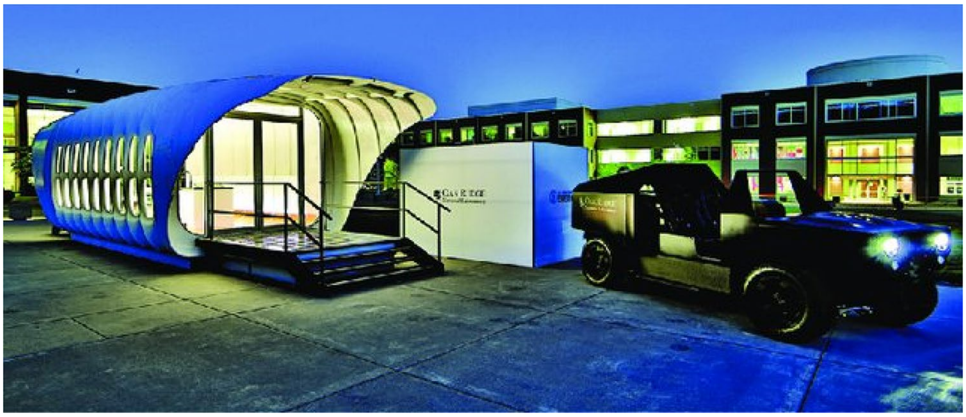

Fig. 9 Additive manufacturing integrated energy demonstration [84]

manufactured molds in ABS reinforced with carbon fiber that have shown a duration about 10 times longer than those obtained with traditional technologies.

4.5 Wind energy systems

With ORNL the startup Hover [141] has 3D printed components of an innovative vertical axis wind turbine capable of capturing more energy than standard ones [87]. These technologies are very advantageous in this application because they would allow one to scale the system easily and with low costs, depending on the context in which it is used.

Another application concerns the manufacturing of a wind turbine blade mold using BAAM technologies [88]. Once printed, the mold was covered with a layer of glass fiber and then used to produce a set of blades (three in total) without causing obvious wear. The use of AM has made it possible to house a heating unit that distributes heat evenly through a system of internal channels (Fig. 10).

4.6 Magnets

It must be considered that permanent magnets are composed of rare elements; therefore, it is important to limit their waste as much as possible during the manufacturing processes. Additive manufacturing technologies can play an important role in this field. In the literature, there are several studies that demonstrate the advantages of 3D printing in the manufacture of permanent magnets.

It has been shown [89] that the performance of isotropic near-net-shape Nd–Fe–B bonded manufactured magnets with BAAM technologies have performances similar or even superior to those made with injection molding, as well as offering advantages related to costs and freedom of shapes and sizes.

The same conclusion was reached in a study in which isotropic bonded 3D printed magnets with a composition of 70% Nd–Fe–B and 30% nylon were mounted on a DC motor to replace the ferrite magnets [90].

It is important to note that the load fraction of the Nd–Fe–B powder in the magnet significantly affects its properties [91], and these can be improved by optimizing the temperature and magnetic field for post-print alignment [92].

5 Conclusion

AM is having an impact on many industries and growing as an alternative or complimentary approach relative to other manufacturing methods, such as formative and subtractive processes. By now, several industrial sectors have explored the benefits of using AM in their activities and, as highlighted, the increase in the build volume of these technologies is essential for their further application in this field.

This paper presents a general review of manufacturing systems for large print volumes, with a focus on pellet-based LFAM systems. Case studies in different industrial sectors have demonstrated the benefits that the use of pellet-based LFAM technologies offer in these fields and should encourage researchers and companies to increase activity in this field. The use of this technology leads to a significant reduction in manufacturing times and costs [28], but it must be considered that it was born a few years ago and still has aspects that can be improved:

- parts with high heights may be subject to dimensional inaccuracies due to due to the vibrations produced by the printer or there may be problems with curling if there is no constant temperature control of the printing chamber.
- during the setting phase, particular attention must be paid to the orientation, the infill, the layer height and the positioning of the supports according to the characteristics of the part that are considered most important: if the production schedule is the limiting factor and strength and surface finish are secondary, parameters to have the maximum print speed must be used, on the other hand, if mechanical strength is the most important factor, different parameters must be used.

Fig. 10 3D printed wind turbine mold by ORNL [88]

- further work is needed to investigate ways to print using multiple materials or combine AM with other processes such as hybrid techniques. The studies presented in this review testify to these needs and demonstrate the great interest from the scientific community in this technology.
- the cost is still high and most of the companies that manufacture and use LFAM systems are located in the USA.

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Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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